ACOUSTIC TO SEISMIC COUPLING
Revision C

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Variables

c_d	=	Speed of sound for longitudinal waves in the ground
ρ	=	Mass density of ground
β	=	Attenuation exponent
A	=	Amplitude
K	=	Empirical constant
P_p	=	Peak sound pressure at ground level
V_p	=	Peak vertical ground velocity
Z	=	Ground impedance
r	=	Radius

Introduction

Seismic vibration can be excited by direct mechanical, explosive or geological events.

Ground vibration can also be excited by airborne acoustical sources, which is the subject of this paper. The source may be a blast; or a rocket engine ignition during liftoff or ground static fire testing.

The highest ground velocity at a given measurement location occurs as the airborne pressure wave passes over for the case of an impulsive source.

Local Ground Response

Consider the local ground vibration near an acoustical source. The source projects a travelling pressure wave. The local ground surface response is assumed to be that of a semi-infinite elastic medium subjected to a stationary by time-varying pressure load.

The peak vertical ground velocity can be calculated from the peak sound pressure via the following impedance relationship.

$$V_p = \frac{P_p}{Z} \tag{1}$$

Note that each of the variables in equation (1) varies with frequency and may be complex, with real and imaginary components.

Empirical ground impedance formulas are given in Reference 1, where the impedance is complex and varies with frequency. This reference also notes that impedance depends on the porosity and flow resistivity of the ground. The flow resistivity is a measure of the ease with which air can move into and out of the ground.

A simple impedance assumption is

$$Z \approx \rho c_d \tag{2}$$

By substitution,

$$V_p \approx \frac{P_p}{\rho c_d} \tag{3}$$

Reference 2 notes that equation (3) will under-predict the true ground velocity because it omits an amplification factor. This amplification occurs because the propagation velocity of the travelling pressure wave will be of the same order of magnitude as the velocity of the seismic waves near the surface.

Sample impedance values are available from China Lake, California and Huntsville, Alabama.

By substitution,

$$V_p \approx \left\{ 0.30 \frac{\text{in}}{\text{psi sec}} \right\} P_p \qquad \text{(China Lake)} \tag{4}$$

$$V_p \leq \left\{ 0.81 \frac{\text{in}}{\text{psi sec}} \right\} P_p \qquad \text{(Huntsville)} \tag{5}$$

Again, equations (4) and (5) omit an amplification factor.

Reference 2 thus gives an alternate formula using an empirical factor K.

$$V_p(f) = K P_p(f) \tag{6}$$

Note that the peak values are assumed to be three times the rms value for each octave band.

Reference 2 determined an empirical factor from a series of acoustic and ground measurements during the launches of the first four Saturn I vehicles from Cape Canaveral.

The recommended upper bound for the empirical factor per Reference 2 is:

$$K = 2.0 \text{ in} / (\text{psi sec}) \qquad \text{(Cape Canaveral)} \tag{7}$$

This value would envelop any amplification effects.

Thus,

$$V_p(f) \leq \left\{ 2 \frac{\text{in}}{\text{psi sec}} \right\} P_p(f) \qquad \text{(Cape Canaveral)} \tag{8}$$

Reference 2 also noted that the maximum horizontal motions were approximately the same as the vertical motion.

Waveforms

Airborne acoustic energy can excite both body and surface waveforms. The four basic types are shown in Appendix B.

An air-coupled Rayleigh wave is a surface wave which is of particular concern. This waveform appears to be more readily excitable by sound sources above the ground than are the other wave types.

Propagation & Attenuation

A simple model for the distance attenuation is

$$A(r) = A_1 \, r^{-\beta} \tag{9}$$

where A_1 is a reference level at 1 meter from the source.

The authors of reference 3 determined the following for a location in Vermont by measurements:

$$\beta = \begin{cases} 1.2 & \text{for summer} \\ 1.9 & \text{for winter} \end{cases} \tag{9}$$

Note that ground was covered with snow for the winter measurement.

In reality, the attenuation exponent should also vary with frequency, but the authors did not account for this.

References

1. E. M. Salomons, Computational Atmospheric Acoustics, Kluwer Academic Publishers, 2001.

2. L.C. Sutherland, Sonic and Vibration Environments for Ground Facilities, NASA Contract NAS8-11217, Wyle Laboratories Research Staff, 1968.

3. D. Albert & J. Orcutt, Observations of Low-frequency Acoustic-to-seismic Coupling in the Summer and Winter, Journal of the Acoustical Society of America (86), July 1989.

4. R. Greenfield & M. Moran, Seismic Acoustic Ratio Estimates Using a Moving Vehicle Source, 1999.

5. D. Albert, Evaluation of Ground Vibrations Induced by Military Noise Sources, US Army Corps of Engineers, Engineering Research and Development Center, ERDC TR-06-5, 2006.

APPENDIX A

China Lake, California

The following data was taken from an explosive test per Reference 2.

$$\rho = 125 \ \frac{\text{lbm}}{\text{ft}^3} = 0.000187 \frac{\text{lbf sec}^2}{\text{in}^4} \quad \text{(A-1)}$$

$$c_d = 1510 \frac{\text{ft}}{\text{sec}} = 18120 \frac{\text{in}}{\text{sec}} \quad \text{(A-2)}$$

$$\rho c_d = 3.4 \frac{\text{lbf sec}}{\text{in}^3} = 3.4 \ \text{psi/in/sec} \quad \text{(A-3)}$$

$$\frac{1}{\rho c_d} = 0.30 \ \frac{1}{\text{psi/in/sec}} \quad \text{(A-4)}$$

Huntsville, Alabama

The following data was taken from rocket engine static fire tests per Reference 2.

$$\rho = 115 \ \frac{\text{lbm}}{\text{ft}^3} = 0.000172 \frac{\text{lbf sec}^2}{\text{in}^4} \quad \text{(A-5)}$$

$$c_d = 600 \frac{\text{ft}}{\text{sec}} = 7200 \frac{\text{in}}{\text{sec}} \qquad \text{(lower bound)} \quad \text{(A-6)}$$

$$\rho c_d = 1.24 \frac{\text{lbf sec}}{\text{in}^3} = 1.24 \ \text{psi/in/sec} \qquad \text{(lower bound)} \quad \text{(A-7)}$$

$$\frac{1}{\rho c_d} = 0.81 \ \frac{1}{\text{psi/in/sec}} \qquad \text{(upper bound)} \quad \text{(A-8)}$$

Fort Greely, Alaska, -15 °C Day

The following result was obtained using a blank pistol shot excitation in Reference 4.

$$K = 10^{-5}\ \frac{\text{m}}{\text{sec Pa}}\left(\frac{39.37\ \text{in/sec}}{\text{m/sec}}\right)\left(\frac{6891}{1\text{psi}}\right) = 2.7\ \frac{\text{in/sec}}{\text{psi}} \qquad \text{(A-9)}$$

U.S. Army, Generic Location

The following average value is given for military equipment-induced noise in Reference 5, page 46, based on experimental results for a variety of locations.

$$K = \left(4.9\,\text{x}\,10^{-6}\ \frac{\text{m}}{\text{sec Pa}}\right)\left(\frac{39.37\ \text{in/sec}}{\text{m/sec}}\right)\left(\frac{6891}{1\text{psi}}\right) = 1.3\ \frac{\text{in/sec}}{\text{psi}} \qquad \text{(A-10)}$$

The same reference also notes that the coupling factor at an individual site may vary between the limits:

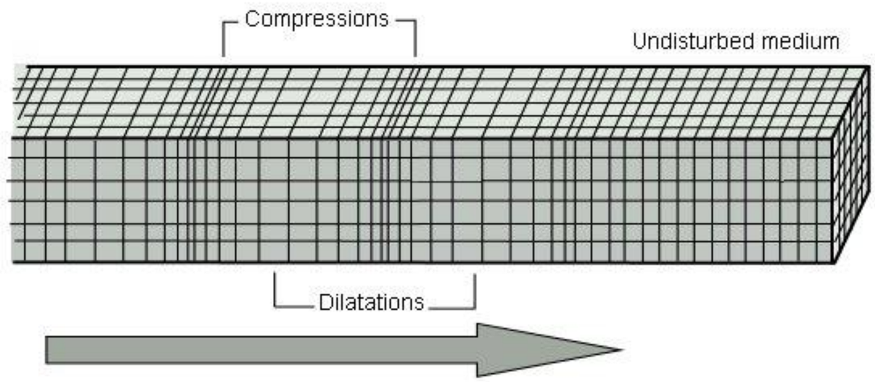
$$0.27\ \frac{\text{in/sec}}{\text{psi}} \le K \le 3.5\ \frac{\text{in/sec}}{\text{psi}} \qquad \text{(A-11)}$$

These limits are given in Reference 5, Abstract, page ii.

APPENDIX B

Seismic Waveforms

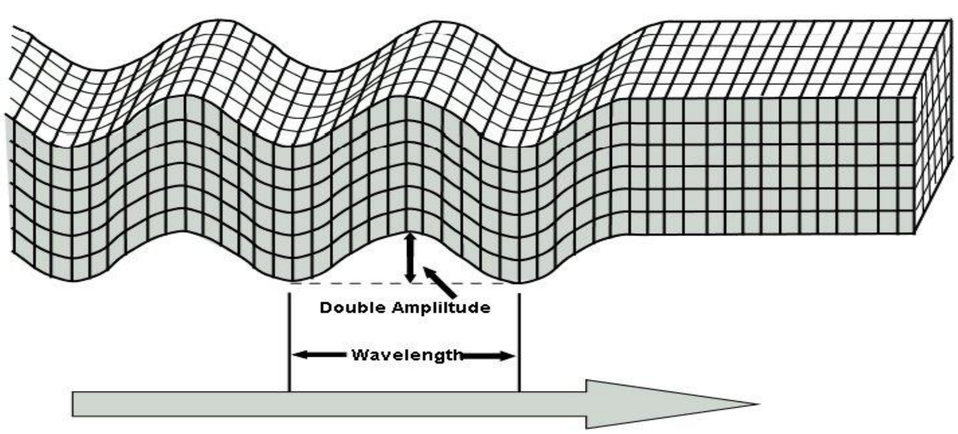
P Wave



The primary wave, or P-wave, is a body wave that can propagate through the Earth's core. This wave can also travel through water.

The P-wave is also a sound wave. It thus has longitudinal motion. Note that the P-wave is the fastest of the four waveforms.

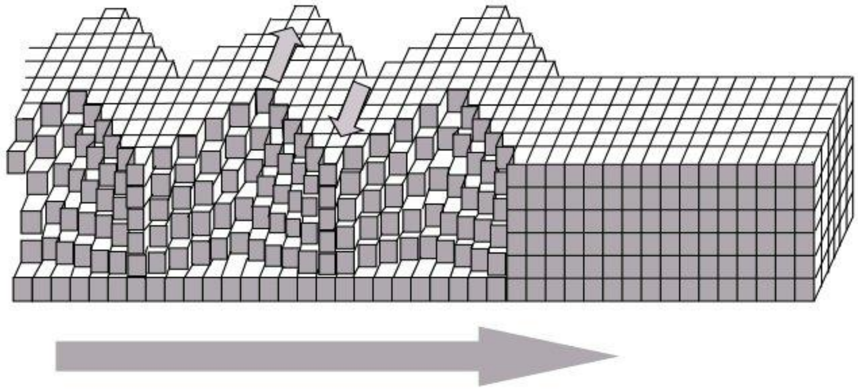
S Wave



The secondary wave, or S-wave, is a shear wave. It is a type of body wave. The S-wave produces an amplitude disturbance that is at right angles to the direction of propagation.

Note that water cannot withstand a shear force. S-waves thus do not propagate in water.

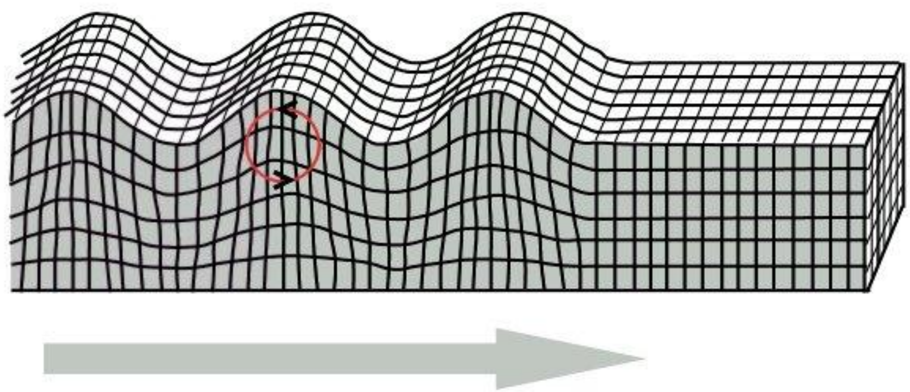
Love Wave



Love waves are shearing horizontal waves. The motion of a Love wave is similar to the motion of a secondary wave except that Love wave only travel along the surface of the Earth.

Love waves do not propagate in water.

Rayleigh Wave



Rayleigh waves travel along the surface of the Earth.

Rayleigh waves produce retrograde elliptical motion. The ground motion is thus both horizontal and vertical. The motion of Rayleigh waves is similar to the motion of ocean waves except that ocean waves are prograde.

Rayleigh waves resulting from airborne acoustical sources may either be prograde or retrograde per Reference 3. In some cases, the motion may begin as prograde and then switch to retrograde.

Rayleigh Wave Dispersion

A material's elastic properties often change with depth. The velocity of a Rayleigh wave is thus dependent on the wavelength and therefore on the frequency.

Rayleigh waves on ideal, homogeneous and flat elastic solids show no dispersion. However, these waves become dispersive if a solid or structure has a density or sound velocity that varies with depth.

One example is Rayleigh waves on the Earth's surface. Those waves with a higher frequency travel more slowly than those with a lower frequency. This occurs because a Rayleigh wave of lower frequency has a relatively long wavelength. The displacement of long wavelength waves penetrates more deeply into the Earth than short wavelength waves.

Since the speed of waves in the Earth increases with increasing depth, the longer wavelength (low frequency) waves can travel faster than the shorter wavelength (high frequency) waves.

Rayleigh waves thus often appear spread out on seismograms recorded at distant earthquake recording stations.

Typical speeds for Rayleigh waves are on the order of 1 to 5 km/s.

Reference: http://en.wikipedia.org/wiki/Rayleigh_wave